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ORIGINAL ARTICLE

Burden of disease attributable to ambient fine particulate matter exposure in Taiwan

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KEYWORDS
ambient fine particulate matter;
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Background/Purpose: There is compelling epidemiological evidence that links air pollution to increased risk of mortality from cardiopulmonary disease and lung cancer. We quantified the burden of mortality attributable to ambient fine particulate matter ($PM_{2.5}$) among the Taiwanese population in 2014 at the national and subnational levels.
Methods: Subnational $PM_{2.5}$ exposure levels were obtained from Taiwan Air Quality Monitoring Network. Relative risks were derived from a previously developed exposure-response model. Population attributable fraction for cause-specific mortality was estimated at the county level using the estimated ambient $PM_{2.5}$ concentrations and the relative risk functions.
Results: In 2014, $PM_{2.5}$ accounted for 6282 deaths [95% confidence interval (CI), 5716–6847], from ischemic heart disease (2244 deaths; 95% CI, 2015–2473), stroke (2140 deaths; 95% CI, 1760–2520), lung cancer (1252 deaths; 95% CI, 995–1509), and chronic obstructive pulmonary disease (645 deaths; 95% CI, 418–872). Nationally, the population attributable mortality fraction of $PM_{2.5}$ for the four disease causes was 18.6% (95% CI, 16.9–20.3%). Substantial geographic variation in $PM_{2.5}$ attributable mortality fraction was found; the percentage of deaths attributable to $PM_{2.5}$ ranged from 8.7% in Hualian County to 21.8% in Yunlin County. In terms of absolute number of deaths, New Taipei and Kaohsiung cities had the largest number of deaths associated with $PM_{2.5}$ (874 and 829 deaths, respectively) among all cities and counties.

Conflicts of interest: The authors have no conflicts of interest relevant to this article.

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Conclusion: Ambient $PM_{2.5}$ pollution is a major mortality risk factor in Taiwan. Aggressive and multisectorial intervention strategies are urgently needed to bring down the impact of air pollution on environment and health.

Introduction

Ambient fine particulate matter ($PM_{2.5}$) exposure is associated with increased mortality.[1] Compelling epidemiological evidence suggests a causal link between $PM_{2.5}$ and mortality from cardiopulmonary disease and lung cancer.[2–5] Using the epidemiological evidence and $PM_{2.5}$ exposure information, the recent Global Burden of Disease (GBD) study (GBD 2013) found that $PM_{2.5}$ accounted for 5.3% of total mortality in 2013, with 2,209,000 deaths from cardiopulmonary diseases and 387,000 deaths from lung cancer.[6]

Risk assessment of $PM_{2.5}$ is important not only at the global and national level but also at the subnational level, because air pollution often varies spatially even at the subnational level. Understanding the impact of $PM_{2.5}$ at the national and subnational level can help development of public health and environmental policies for central and local governments. A previous subnational analysis from the USA revealed a distinct geographic pattern in terms of number of life-years lost and deaths attributable to $PM_{2.5}$.[7] Nevertheless, this type of analysis has never been done in Asian countries where air pollution is the worst among all regions in the world because of economic development and rapid industrialization and urbanization.[8]

In Taiwan, the high coverage of air quality monitoring system and health information system provide an excellent opportunity to assess the public health impact of $PM_{2.5}$. We adopted the comparative risk assessment framework developed by GBD 2010 to quantify the mortality burden attributable to ambient $PM_{2.5}$ air pollution at the national and subnational level in Taiwan.

Methods

We estimated the national and subnational mortality attributable to $PM_{2.5}$ by integrating the information from nationwide air quality monitoring network, national death registry, and the concentration-response functions that linked $PM_{2.5}$ pollution to mortality. We selected four major diseases that are considered causally related to ambient $PM_{2.5}$ in the GBD 2010: ischemic heart disease (IHD), cerebrovascular disease (stroke), lung cancer, and chronic obstructive pulmonary disease (COPD). For each disease we estimated the population attributable fraction (PAF) due to $PM_{2.5}$ using the county-level $PM_{2.5}$ concentration and the GBD-derived relative risk function between ambient $PM_{2.5}$ and specific cause. The PAF was multiplied by the cause-specific number of deaths to obtain the death burden attributable to $PM_{2.5}$, aggregated by county. The analysis was conducted for the year of 2014.

Estimating $PM_{2.5}$ exposure

The annual average of $PM_{2.5}$ concentration was estimated to represent population exposure at the county level using the data from Taiwan Air Quality Monitoring Network.[9] For counties with several monitoring stations, we aggregated data from the air quality monitoring stations in the districts with population density > 10,000 persons/km^2 urban areas (i.e., areas where the population density was the highest) in order to capture the level of air pollution that was representative of the majority at the county level.[10] For counties with limited monitoring stations, we used the measurements located in the city to represent the population exposure for the county. Using these selected data, we calculated annual average and standard error of $PM_{2.5}$ exposure in each county in the year 2014.

Relative risks function

The relative risk (RR) functions between ambient $PM_{2.5}$ and specific causes of deaths were based on the recent estimates in the GBD 2010 analysis (Figure 1).[11] In brief an integrated exposure–response model was developed to allow for nonlinear patterns for the association between $PM_{2.5}$ concentration and corresponding disease causes. The model was fitted to the RR estimates from the published cohort studies. The optimal counterfactual concentration of $PM_{2.5}$ (where RR = 1) was chosen based on the largest cohort study of air pollution (CPS II cohort), with a lower and upper bound of 5.8 μg/m^3 and 8.8 μg/m^3, respectively.

Population attributable fraction

Population attributable fraction (PAF) measures the proportion of disease burden in a given population that would be prevented if the risk factor exposure was shifted to an alternative counterfactual distribution. The following formula was used to compute PAF of a specific disease cause at the county level[12]:

$$PAF_{i,j} = \frac{RR_{c(i),j} - 1}{RR_{c(i),j}}$$

where c(i) is the estimated level of $PM_{2.5}$ concentration in county i; and $RR_{c(i),j}$ is the relative risk for disease j at exposure level c(i) based on the relative risk functions. We multiplied the PAF by the cause-specific number of deaths to obtain the death burden attributable to $PM_{2.5}$.

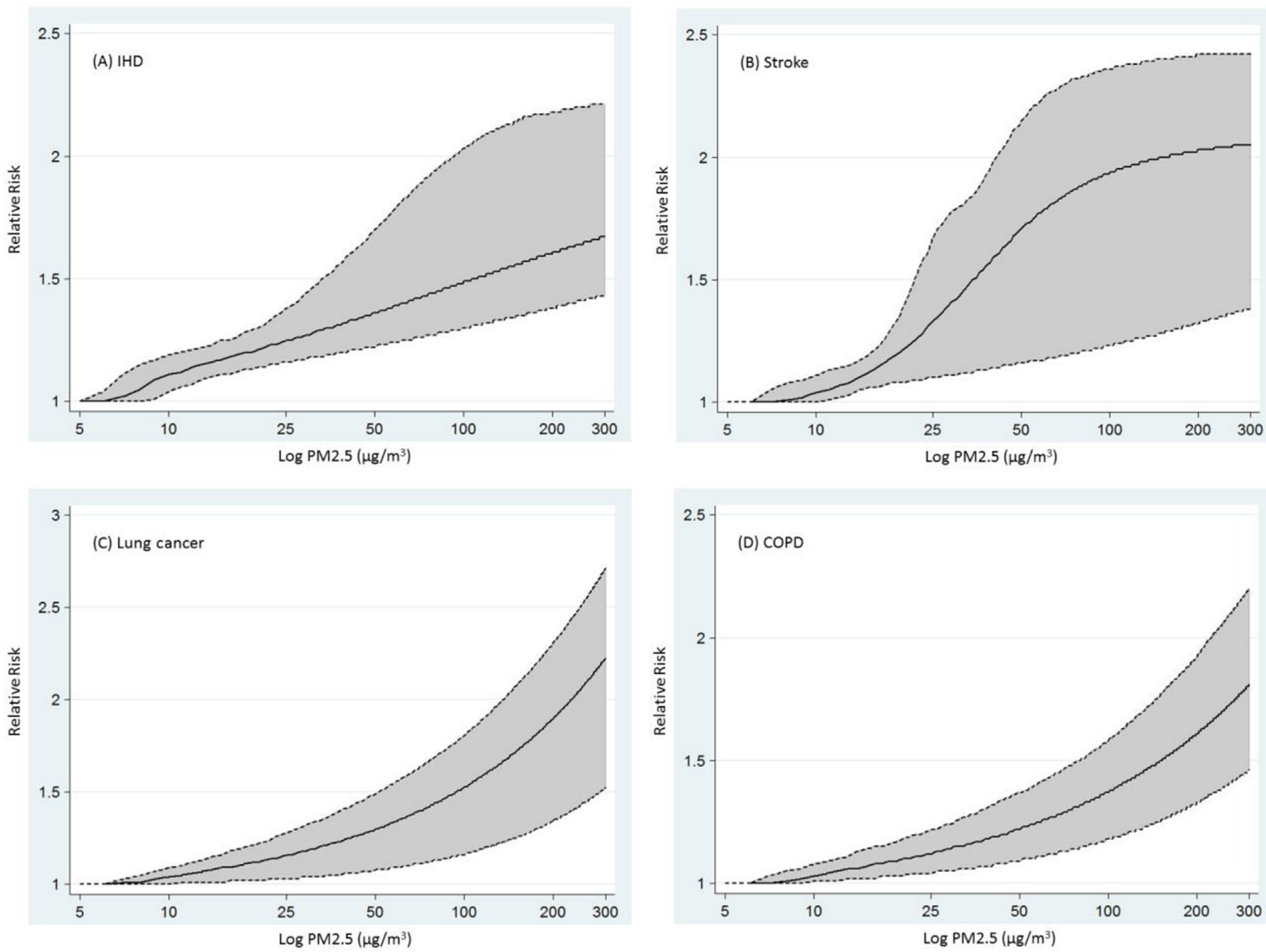

Figure 1 Cause-specific relative risks (solid line) and 95% confidence intervals (broken line and shaded area) for (A) ischemic heart disease (IHD), (B) stroke, (C) lung cancer, and (D) chronic obstructive pulmonary disease (COPD) mortality. $PM_{2.5}$ = fine particulate matter.

County-level mortality data

County-level mortality data for adults aged 25 years and older in 2014 were obtained from the National Death Registry. The disease causes were defined by ICD-10 code: IHD (I20-I25); stroke (I60-I67, I69.0, I69.1, I69.2, I69.3); lung cancer (C33, C34); and COPD (J40-J44). The cause-specific, total attributable deaths, and attributable premature deaths (deaths before the age of average life expectancy at birth in 2014; male, 76.7 years; female, 83.2 years) were estimated by age group, sex, and counties.

Uncertainty analyses

We used statistical simulation to deal with the uncertainty due to sampling variability.[13] We randomly drew 1000 sets of $PM_{2.5}$ exposures and corresponding RRs from the normal distributions of $PM_{2.5}$ concentrations and RRs. Sampling with replacement was used. Each set of sampled $PM_{2.5}$ concentrations and RRs was used to compute the PAF and the number of deaths attributable for each county, separately by age groups. The resulting 1000 PAFs were ranked, and the 2.5th percentile and 97.5th percentile were reported as the 95% confidence intervals (CIs).

Sensitivity analysis

Following the GBD approach, we used the $PM_{2.5}$ data and the mortality data in the same year (2014) to estimate the attributable deaths in the main analysis. The underlying assumption of this analysis was that the $PM_{2.5}$ concentration remained constant over time. Since the levels of $PM_{2.5}$ have been declining in most places of Taiwan[9] and the induction period between air pollution and diseases can be long,[14,15] this approach could have underestimated the attributable deaths due to $PM_{2.5}$.[16] In order to explore the impact of declining air pollution on the attributable mortality estimates, we conducted a sensitivity analysis by using the $PM_{2.5}$ exposure data in 2005 (the earliest comprehensive air quality monitoring data on $PM_{2.5}$) to estimate the attributable death burden in 2014.

Results

Estimated concentration of $PM_{2.5}$ by county

Figure 2 presents the estimated annual average of $PM_{2.5}$ concentrations by county in 2014. The estimated annual average was generally higher in western compared to eastern Taiwan. There was a three-fold difference between the county of the highest $PM_{2.5}$ (34.37 $\mu g/m^3$, Yunlin County) and that of the lowest $PM_{2.5}$ (11.04 $\mu g/m^3$, Taidong County). Notably, the estimates for all counties were above the standard level recommended by the World Health Organization (10 $\mu g/m^3$).

Mortality burden attributable to $PM_{2.5}$

Using the estimated level of $PM_{2.5}$ and the relative risk functions, we calculated the PAF of cause-specific mortality due to $PM_{2.5}$ in each county (Figure 3). In different counties, the PAF ranged from 14.0% to 25.6% for IHD, from 7.8% to 30.7% for stroke, from 4.7% to 17.4% for lung cancer, and from 3.8% to 13.9% for COPD. Nationally, $PM_{2.5}$ was responsible for 6282 (95% CI, 5716—6847) deaths in the year of 2014 (3.8% of all deaths in that year); 4028 of these deaths were premature deaths that occurred before the age of average life expectancy at birth (male, 76.7 years; female, 83.2 years; Figure 4 and Table 1). Among the deaths attributable to $PM_{2.5}$, the leading cause was IHD (2244 deaths; 95% CI, 2015—2473), followed by stroke (2140 deaths; 95% CI, 1760—2520), lung cancer (1252 deaths; 95% CI, 995—1509), and COPD (645 deaths; 95% CI, 418—872). Nationally, the PAF of $PM_{2.5}$ for the four disease causes was 18.6% (95% CI, 16.9—20.3%) in Taiwan, but there was significant geographic variation across the country (Figure 4). Counties from the southwest Taiwan had higher PAF than other counties, with Yunlin City having the highest PAF (21.8%; 95% CI, 19.8—23.7%) in Taiwan. The lowest PAF occurred in Hualian (8.7%) and Taidong (9.1%). In terms of number of deaths, New Taipei and Kaohsiung cities had the largest number of deaths associated with $PM_{2.5}$ (874 and 829 deaths, respectively; Figure 4 and Table 1).

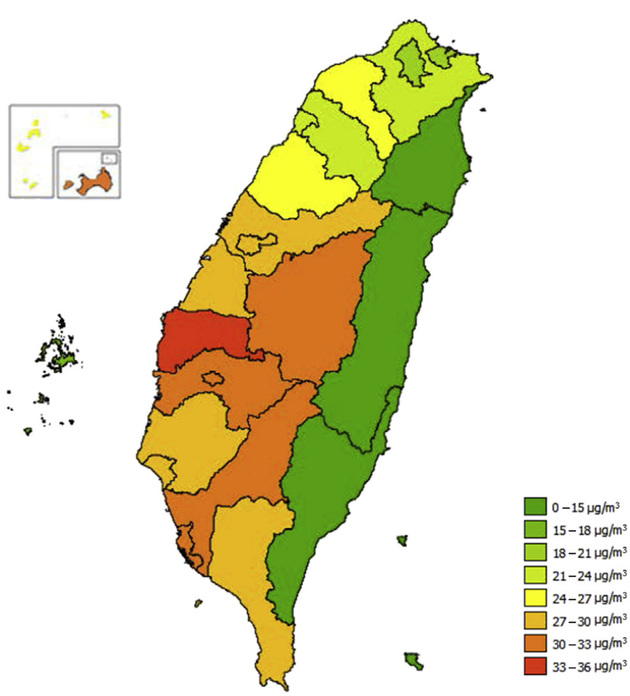

Figure 2 Annual average of fine particulate matter exposure ($\mu g/m^3$) by county, 2014.

Sensitivity analysis

In most counties, the concentration of $PM_{2.5}$ declined between 2005 and 2014 (Figure A1). We conducted a 9-year time lag analysis using the $PM_{2.5}$ concentration in 2005 and the mortality data in 2014 (Table 2). In this sensitivity analysis, the attributable number of deaths from $PM_{2.5}$ was 7869, which was 25.3% higher than the attributable deaths in the main analysis.

Discussion

Using the comparative risk assessment framework of the GBD study, we estimated the burden of disease attributable to $PM_{2.5}$ at national and subnational level by integrating the nationwide air quality monitoring data and the vital statistics. We found that in 2014, more than 6000 deaths from IHD, stroke, lung cancer, and COPD in Taiwan could be attributable to $PM_{2.5}$. Nationally nearly one fifth of deaths from the four major disease causes were due to $PM_{2.5}$. Substantial geographic variation in attributable fraction was also noted, with the southwest Taiwan having the highest attributable fraction. Major metropolitan areas, including New Taipei and Kaohsiung cities, accounted for the largest number of attributable deaths from $PM_{2.5}$.

Our national estimate was consistent with the Taiwan estimate reported in GBD 2013. In GBD 2013, the number of deaths attributable to $PM_{2.5}$ in Taiwan was 7526, and 26.6% of these deaths were from IHD, 26.3% from lung cancer, 23.4% from stroke, and 3.2% from COPD.[6] In the GBD analysis, satellite imagery and atmospheric models were used to derive $PM_{2.5}$ estimates, while the ground-level monitoring network was used to estimate $PM_{2.5}$ concentrations in present study. The satellite-based estimates have been demonstrated to be consistent with ground-based estimates, with the correlation coefficient ranging from 0.58 to 0.96 under various conditions.[17—22] One advantage of the present study was that we used the county-level mortality data (instead of the national mortality data in the GBD analysis). Therefore our analysis provided subnational information that was relevant for local government and national information that was more accurate than the previous estimate.

In Taiwan, the $PM_{2.5}$ exposure has been decreasing in most areas in recent years. The estimated national average of $PM_{2.5}$ exposure declined from 36.2 $\mu g/m^3$ in 2005 to 25.0 $\mu g/m^3$ in 2014. However, the current level of $PM_{2.5}$ exposure is still far from the optimal level that has minimal health risk.[23,24] Indeed our analysis revealed substantial mortality burden attributable to $PM_{2.5}$ exposure. Unlike behavioral and physiological risk factors, people in the same area share a similar pattern of $PM_{2.5}$ exposure, which

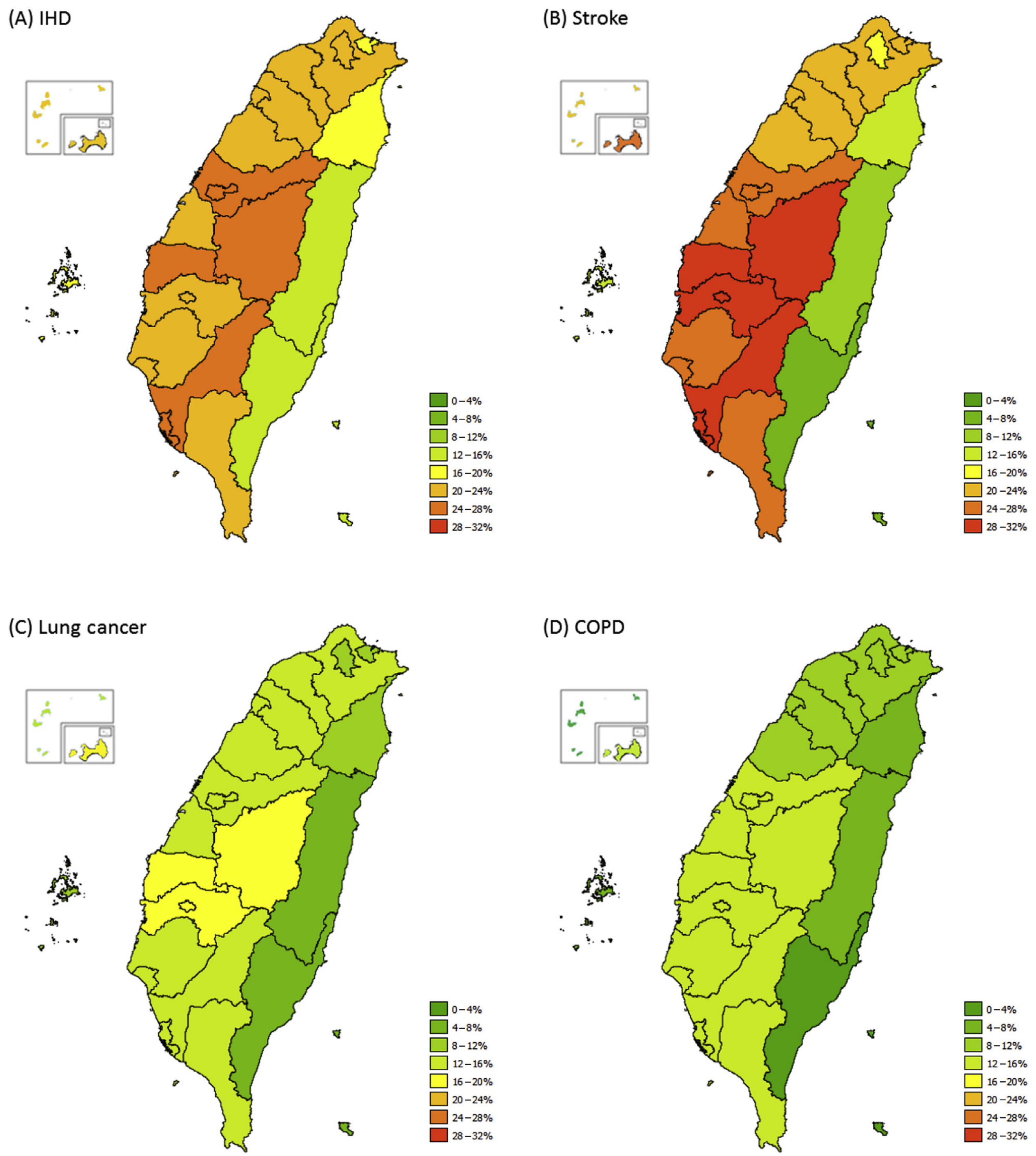

Figure 3 Subnational analysis of population attributable fraction of fine particulate matter by disease cause, 2014. (A) Ischemic heart disease, (B) stroke, (C) lung cancer, and (D) chronic obstructive pulmonary disease.

is difficult to avoid by personal effort. The Government plays a critical role in the control of environmental risk factors such as ambient air pollution.

Our analysis revealed substantial geographic variation in terms of $PM_{2.5}$ exposure and attributable mortality fraction due to $PM_{2.5}$. A previous study in the USA also found unequal spatial distribution in health risk of air pollution.[7] These spatial variations are directly linked to levels of urbanization, industrial emissions, and pollutant transmission. Nonetheless, the striking difference in $PM_{2.5}$ exposure and its health effects across Taiwan has major implications on social inequalities in environment and health. Recently the Health Promotion Administration set a priority to reduce health inequality in the country. Our analysis strongly suggests that health promotion cannot be separated out from environmental and economic factors. We urge that a coordinated, multisectorial effort that involves at least Ministry of Health and Welfare, Environmental Protection

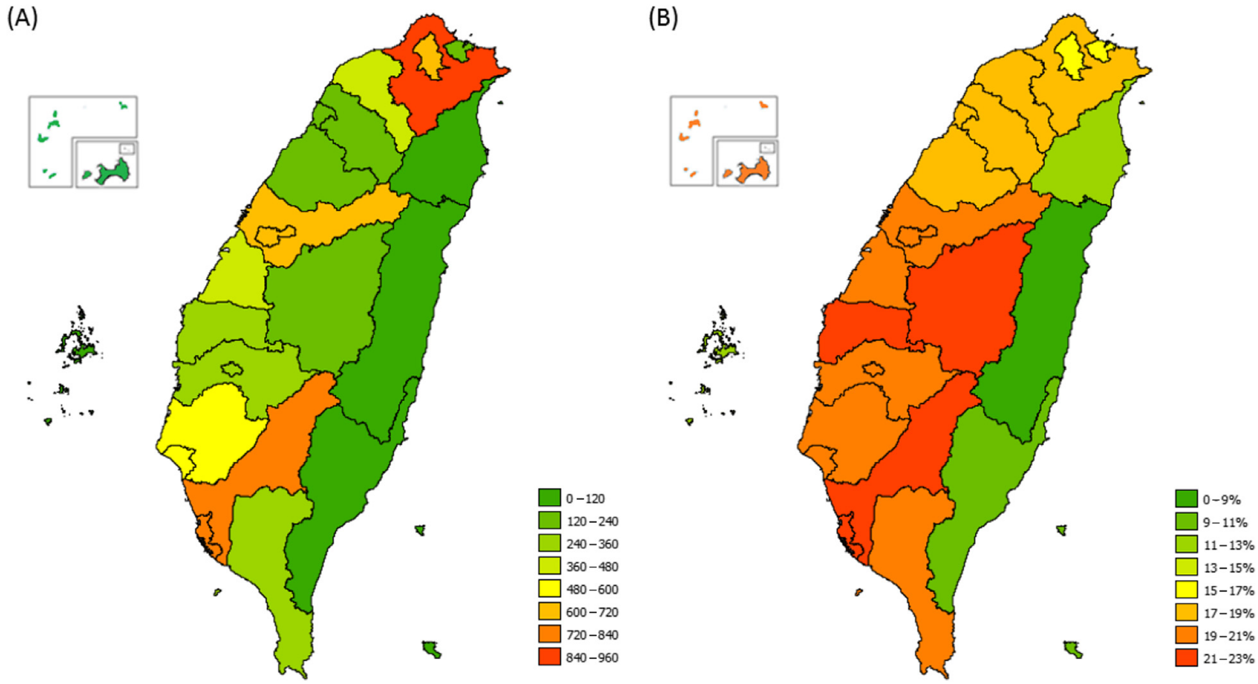

Figure 4 Subnational analysis of mortality burden attributable to fine particulate matter, 2014. (A) Attributable number of deaths; and (B) population attributable fraction combining ischemic heart disease, stroke, lung cancer, and chronic obstructive pulmonary disease.

Table 1 National and subnational analysis of number of deaths attributable to $PM_{2.5}$ by disease cause, 2014.

County	IHD	Stroke	Lung cancer	COPD	Total deaths	Premature deaths[a]
	n 95% CI	*n* 95% CI	*n* 95% CI	*n* 95% CI	*n* 95% CI	*n* 95% CI
Keelung	70 (63–77)	28 (24–33)	18 (14–22)	8 (5–12)	124 (115–134)	81 (75–87)
Taipei	283 (255–311)	176 (143–209)	106 (80–132)	54 (30–79)	619 (563–675)	367 (342–393)
New Taipei	365 (331–398)	271 (225–317)	165 (131–200)	73 (46–101)	874 (802–946)	584 (542–627)
Taoyuan	134 (121–148)	172 (140–205)	84 (66–102)	38 (23–54)	429 (387–471)	269 (248–290)
Hsinchu	76 (67–84)	91 (73–108)	35 (27–42)	18 (11–25)	220 (198–242)	134 (123–144)
Yilan	45 (39–50)	26 (21–31)	19 (15–24)	10 (5–15)	100 (90–110)	61 (56–66)
Miaoli	69 (62–76)	74 (60–87)	30 (23–36)	19 (12–27)	191 (173–210)	117 (107–126)
Taichung	193 (176–211)	220 (180–260)	132 (108–157)	68 (43–92)	613 (557–669)	399 (369–430)
Jhanghua	124 (111–138)	147 (122–172)	97 (76–117)	47 (32–63)	415 (377–454)	262 (241–284)
Nantou	59 (53–66)	80 (67–92)	41 (33–49)	33 (22–43)	213 (193–232)	136 (125–147)
Yunlin	111 (98–123)	105 (86–124)	73 (60–87)	36 (25–47)	325 (296–354)	203 (187–218)
Chiayi	100 (87–112)	105 (85–124)	76 (61–92)	39 (26–53)	320 (289–351)	185 (171–200)
Tainan	155 (140–171)	197 (161–232)	120 (97–142)	60 (41–79)	531 (483–580)	342 (314–370)
Kaohsiung	286 (258–314)	283 (239–328)	178 (144–211)	82 (58–106)	829 (762–896)	570 (529–612)
Pingdong	104 (94–115)	119 (99–139)	55 (44–65)	46 (32–60)	324 (296–352)	215 (199–232)
Magong	9 (8–10)	6 (5–7)	5 (3–6)	1 (1–2)	22 (20–24)	14 (13–15)
Hualian	21 (18–24)	18 (14–23)	7 (5–9)	6 (3–9)	52 (46–59)	33 (29–36)
Taidong	27 (23–31)	11 (8–15)	5 (4–7)	3 (2–5)	47 (42–53)	35 (31–39)
Kinmen	11 (10–12)	10 (8–12)	7 (5–8)	2 (1–3)	30 (27–33)	19 (17–20)
Matsu	1 (1–2)	1 (1–1)	1 (0–1)	0 (0–0)	3 (2–3)	2 (2–2)
Taiwan	2244 (2015–2473)	2140 (1760–2520)	1252 (995–1509)	645 (418–872)	6282 (5716–6847)	4028 (3719–4338)

CI = confidence interval; COPD = chronic obstructive pulmonary disease; IHD = ischemic heart disease.
[a] Death before that age of average life expectancy at birth.

Table 2 Number of deaths attributable to $PM_{2.5}$ by county, comparing the main analysis and the analysis using 9-year time lag.

County	Main analysis	9-y time lag
	n 95% CI	*n* 95% CI
Keelung	124 (115–134)	146 (134–159)
Taipei	619 (563–675)	818 (742–895)
New Taipei	874 (802–946)	1108 (1020–1196)
Taoyuan	429 (387–471)	532 (483–582)
Hsinchu	220 (198–242)	268 (242–295)
Yilan	100 (90–110)	134 (121–147)
Miaoli	191 (173–210)	220 (199–242)
Taichung	613 (557–669)	750 (688–813)
Jhanghua	415 (377–454)	512 (468–555)
Nantou	213 (193–232)	229 (209–250)
Yunlin	325 (296–354)	374 (343–406)
Chiayi	320 (289–351)	388 (354–423)
Tainan	531 (483–580)	662 (607–717)
Kaohsiung	829 (762–896)	1053 (977–1129)
Pingdong	324 (296–352)	447 (413–481)
Magong	22 (20–24)	30 (27–33)
Hualian	52 (46–59)	89 (80–98)
Taidong	47 (42–53)	70 (64–76)
Kinmen	30 (27–33)	33 (30–36)
Matsu	3 (2–3)	3 (3–4)
Taiwan	6282 (5716–6847)	7869 (7204–8534)

CI = confidence interval.

Agency (EPA), and Ministry of Economic Affairs will be needed to act on the complex but urgent issue of air pollution and health.

We found a concerning high proportion of deaths from IHD, stroke, lung cancer, and COPD due to $PM_{2.5}$ exposure in central and southwest Taiwan. The high level of $PM_{2.5}$ exposure in central and southwest Taiwan was primarily due to emissions from coal-fired power plants and heavy industry factories.[25–27] Coal-fired power plants and petrochemical industries have been identified as an important source of PM emissions in central Taiwan.[27,28] It has been suggested that Nantou County, a county without major sources of PM emission, suffered from PM emission from neighboring counties.[9] By contrast, as a harbor city situated in southern Taiwan, Kaohsiung has long been the center of Taiwan's heavy industries in recent decades. The air pollution affects not only the Kaohsiung city but also the surrounding counties, especially the Ping-Tong County. A regional strategy to control total amount of air pollution emitted from all sources of Kaoshung and Ping-Tong counties is needed to lower $PM_{2.5}$ exposure of the residents there. The recent policy, promulgated by Taiwan EPA, to designate a maximum amount of emissions from existing and new sources in the Kaoshung and Ping-Tong counties is a right step towards tackling the severe air pollution problem in this region.

Several limitations and uncertainties of our analysis warrant discussion. First, the relative risk functions used in this study were obtained from the global estimates in the GBD study. Because of the limited number of Asian studies on the long-term health effect of ambient air pollution, the majority of epidemiologic evidence was based on studies from North America and Europe.[29] However, the results from studies in Hong Kong and China on air pollution and cardiorespiratory mortality were consistent with the observation in the Western population.[30,31] Local evidence on the long-term health effect of ambient air pollution is still badly needed for Taiwan. Second, our study focused on the death burden attributable to $PM_{2.5}$, but the impact on morbidity and disability was not accounted for. Since advancements in medicine and technology have prolonged life expectancy and decreased premature deaths, it would be necessary to include nonfatal disease outcomes and disability adjusted life-years in future assessment. Also, it should be noted that $PM_{2.5}$ concentrations measured by automatic monitoring instruments in Taiwan may either overestimate or underestimate PM levels measured by manual monitoring instruments in the United States depending on the humidity at the time air pollution levels are measured at various locations in Taiwan. Accordingly, PAF of $PM_{2.5}$ in Taiwan may be either overestimate or underestimated by such difference. For consistency in assessing disease burdens of air pollution across counties within Taiwan as well as across countries globally, we deem current PAF of $PM_{2.5}$ is the most reasonable estimate we can derive. Moreover, it is also statistically possible to estimate township-specific rather than county-specific PAF of $PM_{2.5}$ by applying spatial interpolation techniques, such as ordinary Kriging, to air monitoring data, assuming people's air pollution exposure was the same as spatially dispersed contours of pollution levels. Nonetheless, we note that our approach is less likely to be substantially affected by the geographic heterogeneity of $PM_{2.5}$ level, since the estimated $PM_{2.5}$ level was based on the more densely populated urban areas. In addition, we only included the disease outcomes with robust epidemiological evidence. Emerging evidence suggests that ambient air pollution might be associated with outcomes other than cardio-respiratory mortality, such as diabetes mellitus, Alzheimer's disease, tuberculosis, and chronic kidney disease.[32–35] Our analysis is therefore a conservative assessment of the health impact of ambient air pollution. Finally, the $PM_{2.5}$ exposure and mortality data in the same year were used to estimate the disease burden in the present study. We conducted a 9-year time lag analysis to explore the extent of underestimation of the effect of air pollution. We note, however, that the actual induction period for certain disease outcome (e.g., lung cancer) might be longer than 9 years.

The 68th World Health Assembly recently adopted a resolution to address the health impacts of air pollution—the world's largest single environmental health risk. Our study clearly concludes that air pollution, especially $PM_{2.5}$, is an important, yet preventable public health problem in Taiwan. Our findings imply that the Taiwan Environmental Protection Administration needs to set a more stringent $PM_{2.5}$ standard in order to protect public health. The Ministry of Health and Welfare needs to play a more active role in raising awareness about the potential to save lives and reduce health costs of air pollution in Taiwan. The Ministry of Health and Welfare also needs to build strong cooperation with the Ministry of Economic Affairs in order to assure that health concerns of air pollution will be integrated into all national, regional, and local economic development policies. Last but not least, the Ministry of Health and Welfare should establish a public health system of combining air quality monitoring systems with health registries to improve surveillance for all illnesses related to air pollution.

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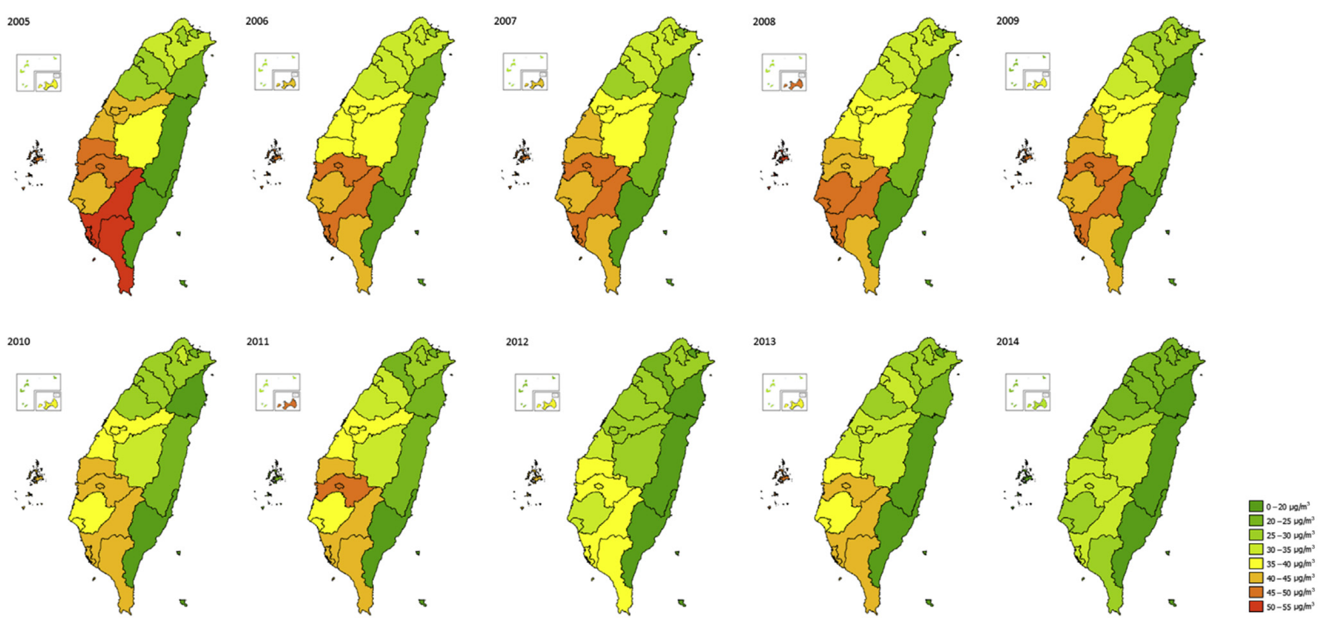
Appendix

Figure A1. Annual average of fine particulate matter exposure ($\mu g/m^3$) by county, from 2005 to 2014.



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